

A MISSION TO TEST THE PIONEER ANOMALY¹

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Analysis of the radio tracking data from the Pioneer 10/11 spacecraft has consistently indicated the presence of an anomalous small Doppler frequency drift. The drift can be interpreted as being due to a constant acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2$ directed *towards* the Sun. Although it is suspected that there is a systematic origin to the effect, none has been found. The nature of this anomaly has become of growing interest in the fields of relativistic cosmology, astro- and gravitational physics as well as in the areas of spacecraft design and high-precision navigation. We present a concept for a designated deep-space mission to test the discovered anomaly. A number of critical requirements and design considerations for such a mission are outlined and addressed.

PACS: 04.80.-y, 95.10.Eg, 95.55.Pe

¹ This essay received an honorable mention in the Annual Essay Competition of the Gravity Research Foundation for the year 2002 — Ed.

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1 The Pioneer Missions and the Anomaly

The Pioneer 10/11 missions, launched on 2 March 1972 (Pioneer 10) and 4 Dec 1973 (Pioneer 11), were the first to explore the outer solar system [1]. After Jupiter and (for Pioneer 11) Saturn encounters, the two spacecraft followed escape hyperbolic orbits near the plane of the ecliptic to opposite sides of the solar system. Pioneer 10 eventually became the first man-made object to leave the solar system.

Pioneer 10's radio signal is weakening. Despite this, the Deep Space Network (DSN) is still able to deliver navigational data from distances ~ 80 AU. Indeed, on the 30th anniversary of its launch, 2 March 2002, the Madrid DSN station received a return radio signal from Pioneer 10 at 22:47 CET. This was 22 h 06 m after the uplink signal was sent from the Goldstone, CA, DSN station.

By 1980, when Pioneer 10 was at a distance of ~ 20 AU from the Sun, the acceleration contribution from solar-radiation-pressure on Pioneer 10 (directed *away* from the Sun) decreased to $< 5 \times 10^{-8}$ cm/s². At that point the navigational data began to clearly indicate the presence of an anomaly in the Doppler navigational data, which was later interpreted as a constant acceleration, a_P , directed *toward* the Sun [2].

Recently, we published a detailed study of the Pioneer anomaly, which used the existing Pioneer 10/11 Doppler data from 1987.0 to 1998.5. We specifically addressed all possible sources for a systematic origin for the detected anomaly. Our conclusion was that, even after all *known* systematics are accounted for, there remains an anomalous acceleration signal of $a_P = (8.74 \pm 1.33) \times 10^{-5}$ cm/s² directed *towards* the Sun [3].

We emphasize “*known*” because we must admit that the most likely cause of the effect is some as yet not understood systematic generated by the spacecraft themselves, perhaps caused by excessive heat or propulsion gas leaks. But neither we nor others with spacecraft or navigational expertise have been able to find it [3].

Further, due to its different mission and spacecraft designs, as well as its proximity to the Sun, the use of the Cassini spacecraft to test for the anomaly proved to be impractical.

A number of alternative ground-based verifications of the anomaly were also considered; for example, using Very Long Baseline Interferometry (VLBI) astrometric observations. However, the trajectory of Pioneer 10, with a small proper motion on the sky, makes it presently impossible to accurately isolate the anomalous Sun-ward acceleration.

Therefore, we strongly argue that the time has come to consider a new deep-space experimental test of this intriguing effect.

2 The Mission

When considering any space mission one needs to address a number of important issues, such as (i) the scientific justification for the mission objectives; (ii) the mission configuration and design requirements; and (iii) the overall construction, launch, and ground operations cost. The scientific justification for our mission is clearly outlined above.

The cost would be the most constraining factor. Almost any deep-space mission would now cost on the order of M\$300-500 [4]. Therefore, a test of the Pioneer effect might best be considered as a relatively small part of another dedicated mission whose objective is to study the boundaries of the solar system.

First, one needs to be at a distance greater than 20 AU to be able to best distinguish any effect from solar radiation pressure and other near-solar systematics. Therefore, a very energetic rocket would be helpful. We observe that the Russian Proton rocket is an intriguing possibility. Indeed, this might be a useful option for international collaboration and to hold down the cost to NASA [5]. Further, NASA has renewed interest in nuclear rockets [6]. This might enable faster missions to the outer solar system.

Non-gravitational forces acting on spacecraft are common and they can cause problems for precision space navigation. So, once in deep space one needs to have a spacecraft with very small or else well-understood systematics. Therefore, an anomaly test could well impose stringent design constraints. To better understand what is needed, it is useful to keep in mind the design of the Pioneer craft and to understand what made them

To be a simple spinner, the craft with its equipment will have to be moment-of-inertia balanced about the main antenna axis. This can be aided by having the Radioisotope Thermoelectric Generators (RTGs), which generate the electrical power, on extended booms that are deployed after launch.

However, other mission objectives might necessitate a 3-axis stabilized spacecraft. If so, then in order to achieve comparable navigational accuracy one would need to develop and fly long-lasting accelerometers, very precise fuel gages, and well-calibrated thrusters.

Finally, dual stabilization might be used; 3-axis near encounters and spin stabilized on cruise, as was done for Galileo. In any event, one wants spin-rate control and/or accelerometers that would yield measurements accurate to the level of the Pioneer navigational error, $\mathcal{O}(10^{-9})$ cm/s² [in other units, $\mathcal{O}(10^{-12})$ g = $\mathcal{O}(10^{-3})$ μ Gal].

On-board power system: RTGs are the only viable choice for deep space power, so international cooperation might again be useful. Due to environmental politics (recall the Cassini Earth-flyby furor) the USA no longer makes ²³⁸Pu for RTGs. This could change with NASA's new nuclear initiative [6], but for now, Russia is the only source.

Heat rejection and thermal control: The RTGs bring up the other main systematic in deep space, thermal emission generated by the spacecraft's power system. One reason the Pioneer RTGs were placed on booms was fear of gamma radiation damage to the spacecraft electronics and surface. This turned out not to be a problem but the placement was serendipitously lucky. The RTGs, with $\sim 2,500$ W of heat, were placed where they would have little thermal effect on the craft. (The Pioneer effect could be caused by only 63 W of directed power radiating from the 241 kg craft.) The rotation of the craft and the RTG fin structures were designed to radiate symmetrically fore-aft, with much less heat radiated in the direction towards the craft. The same concept should be used for this mission, with perhaps shielding of the craft to prevent anisotropic heat reflection.

The electrical power in the equipment and instrument compartments must be radiated

so as to not cause an undetected systematic. For the Pioneers the central compartment was surrounded by insulation with louvers aft to let out excess heat early in the mission, and to retain heat later on when the electrical power was less. The electrical power degrades faster than the radioactive decay because the thermoelectric devices deteriorate.

For this mission, the louvers should be on the side of the compartment so they will radiate in an axially symmetric manner as the spacecraft rotates. The top and bottom of the compartment should also be insulated to further minimize the heat transfer and reflection. The booms connecting the compartment to the antenna as well as the booms to the RTGs should be thermally isolated, either with insulators in the structure or by using appropriate materials in the construction. As good as possible a priori thermal models should be created and test-stand measurements and calibrations should be made.

Communications: Even with all systematics known, no good data is possible without good navigation. This implies the use of both Doppler and range data. The Doppler tracking, which measures the velocity of the craft, should be done at two frequencies, say X-band and Ka-band. The two frequencies are useful to correct for dispersive media effects and will allow precise calibration of plasma systematics. But the Doppler technique only indirectly measures distance to the craft, by integrating the measured Doppler velocity from known initial conditions. Range itself is a time-of-flight measurement. This is done by phase modulating the signal and timing the return signal, which was transponded at the craft. As such, it gives the distance to the spacecraft directly.

Three-dimensional tracking: Having both Doppler and range would allow a very precise orbit to be determined, especially if VLBI were used. Indeed, one might be able to obtain good three-dimensional acceleration data. This latter would be very desirable for detailed acceleration anomaly searches. One would expect that an internal systematic would be directed along the craft spin axis, an anomalous new force would be directed towards the Sun, an external drag force would be almost along the velocity vector, and

a time acceleration would be directed towards the Earth. Having three-dimensional tracking might allow a differentiation to be made from among these four directions.

Turning the spacecraft around: We also propose an experiment which would clearly determine how much, if any, of an anomaly were due to systematics. Suppose one had an additional antenna in the forward direction, appropriate care taken of the mounting of the craft to the launch vehicle. (One would also continuously transmit from both antennas to reduce the radio-power systematic.) Then, aided by Sun and star sensors, if one rotated the spacecraft by 180° so that the forward antenna faced the Earth, any systematic would be in the opposite direction whereas an acceleration due to an exterior force would not. A very similar rotation was actually performed on Pioneer 10 soon after launch, the Earth acquisition precession. For a craft like the Pioneers such a maneuver could be done in about two hours and take about 0.5 kg of fuel [7].

Finally, if the Pioneer anomaly is due either to “normal gravity,” or to “non-gravitational force” but not to systematics, it can be measured by Doppler and range. But accelerometers, used as feed back to control non-gravitational forces, would distinguish between the two types of forces. (Modified inertia [8], violating the strong equivalence principle, might also be addressed.)

3 Summary

Since future space missions will require accurate navigation and/or positioning, it is important that we gain an understanding of the Pioneer anomaly. For instance, the Space Interferometry Mission (SIM) and the Laser Interferometric Space Antenna (LISA) [and possibly even a mission to Pluto and the Kuiper Belt] want navigation to a precision less than that which would be caused by the Pioneer anomaly. In particular, if the Pluto/Kuiper mission goes, it would be fortunate if the craft were designed so as to be able to repeat the Pioneer measurement beyond 20 AU.

It is our personal hope that the next generation of deep space missions will utilize a much greater navigational accuracy and precision. Then, independent of whether the Pioneers measured a systematic effect generated by the spacecraft or (unlikely as it is) a manifestation of “new physics,” an experiment to test the result would be important and should be done [9]. If, as is probably the case, the anomaly is due to some systematic, understanding this will greatly aid future mission design and navigational programs. But if, on the other hand, there is something unknown going on, the implications are obvious.

Acknowledgments

We first express our deep appreciation of the insights obtained from our colleagues in the study of the Pioneer anomaly, Philip A. Laing, Eunice L. Lau, and the late Tony S. Liu. for this work, David Lozier [7] of NASA/Ames was particularly helpful. The work of J. D.A. and S.G.T was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. M.M.N. acknowledges support by the U.S. DOE.

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- [4] For costs of the Discovery Series and the Pluto/Kuiper Belt mission go to, e.g., <http://discovery.nasa.gov/overview.html> and <http://spacelink.nasa.gov/NASA.News/NASA.News.Releases/Previous.News.Releases/>

then click on “00.i2 News Releases” followed by “00-12-20 Proposals for Pluto Mission.”

- [5] In the best case, probes would be sent in three directions: parallel to the Solar system galactic motion, towards the galactic center, and perpendicular to the ecliptic plane.
- [6] W. T. Huntress, Jr., DPS (of AAS) Mailing #02-04, 11 Feb. 2002. See:
http://www.aas.org/~dps/MISC_NOTICES/020211_nasa_budget.html
- [7] We thank David Lozier of NASA/Ames Research Center for giving us information on the Earth precession maneuver of the Pioneer 10 craft and how a maneuver such as we envision could be done.
- [8] See, e.g., M. Milgrom, eprints astro-ph/0207231, astro-ph/0112069, and references therein.
- [9] This point has also just been made in O. Bertolami and M. Tajmar, gr-qc/0207123; Sec. 12.4 of *Gravity Control and Possible Influence on Space Propulsion - a Scientific Study*, ESA - ESTEC Contract 15464/01/NL/SFe, April 2002.